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HIGH-G GIMBAL TECHNOLOGY STUDIES

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Technology Laboratory

July 1979

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1. INTRODUCTION.

A stabilized gimbal platform carried by a high velocity projectile for supporting a terminal homing sensor is a desirable requirement for future applications. The objective of this task is to study the gimbal technology and predict feasible concepts worthy of demonstrating a two-axes wide angle stabilized gimbal system. Acceleration environments for the high velocity projectiles are of such intensities that special bearing protection design technology is required to develop a cannon type launchable gimbal system.

The rationale used in developing high-g platform technology is based on the following primary requirements:

A. The gimbal concept must be an uncomplicated, low cost design which has high probability of surviving a 10,000 g cannon launch shock.

B. The gimballed seeker assembly must fit within the size and shape of a 155 millimeter envelope so that the sensor diameter is at least 76 millimeters with a desired diameter of 108 millimeters.

C. The stabilized sensor must precess simultaneously with the inertial reference, and also, it must be decoupled from the spinning gyroscopic element.

D. The gimbal system must support a sensor element weighing 1.8 kilograms or less.

E. The gimbal system must withstand a 10,000 g longitudinal load, a concurrent 800 g transverse peak launch acceleration and a reverse load of 1,000 g's.

F. The platform must provide a gimbal angular freedom of at least +45 degrees; -25 degrees in one plane, and, at least ± 25 degrees in the orthogonal plane.

G. The operational mission time for the stabilizing element must be a minimum of 70 seconds once the unit has survived the launch shock.

H. The stabilized sensing element must be capable of being torqued in response to input commands at rates up to 10 degrees per second.

I. Gimbal position transducers are required to measure the angular displacement of each gimbal relative to the air frame.

J. There will be at least four sensor cables which must cause minimum impediment on platform performance.

These requirements are the basic guidelines that will be used in developing the high-g platform technology. Other important key factors considered in the studies are performance parameters, cost, and risk, combined with high probability of surviving the high-g launch environment.

Two gimbal mechanizations are considered in the technology studies: the Cardan and the Hooke's Joint Concepts.

2. CONCEPT HIGH-G GIMBAL TECHNOLOGY STUDIES.

A. CARDAN MECHANIZATION AND BEARING PROTECTION DEVICE.

The first mechanization studied is the Cardan Concept as illustrated in Figure 1. This concept allows the inner gimbal to be used as the mounting frame for both the stabilizing element and the sensor. This concept allows the sensor to be conveniently decoupled from the gyroscopic element and the sensor will precess with the inertial element because it is mounted on the same gimbal.

The Cardan Concept offers a two-axes momentum stabilized ball bearing gimbal design which incorporates compliant mounts around the gimbal bearings. These mounts allow the total weight of the gimbal assembly to be absorbed by the gyro housing without damage to the bearings. To accomplish this, both the inner and outer gimbal bearings are mounted in a compliant bearing housing design using compliant material as the Lord Corporation Broad Temperature Range Elastomer. This type of material is usable because of its high internal damping properties, tensile strength, and tear resistance. Also, it functions effectively over the temperature range of -50 degrees centigrade to 150 degrees centigrade. The material also has the load deflection characteristics necessary for this application.

As shown in Figure 1, a gimballed platform includes a sensor (12) mounted on a hemispherical inner gimbal (14).

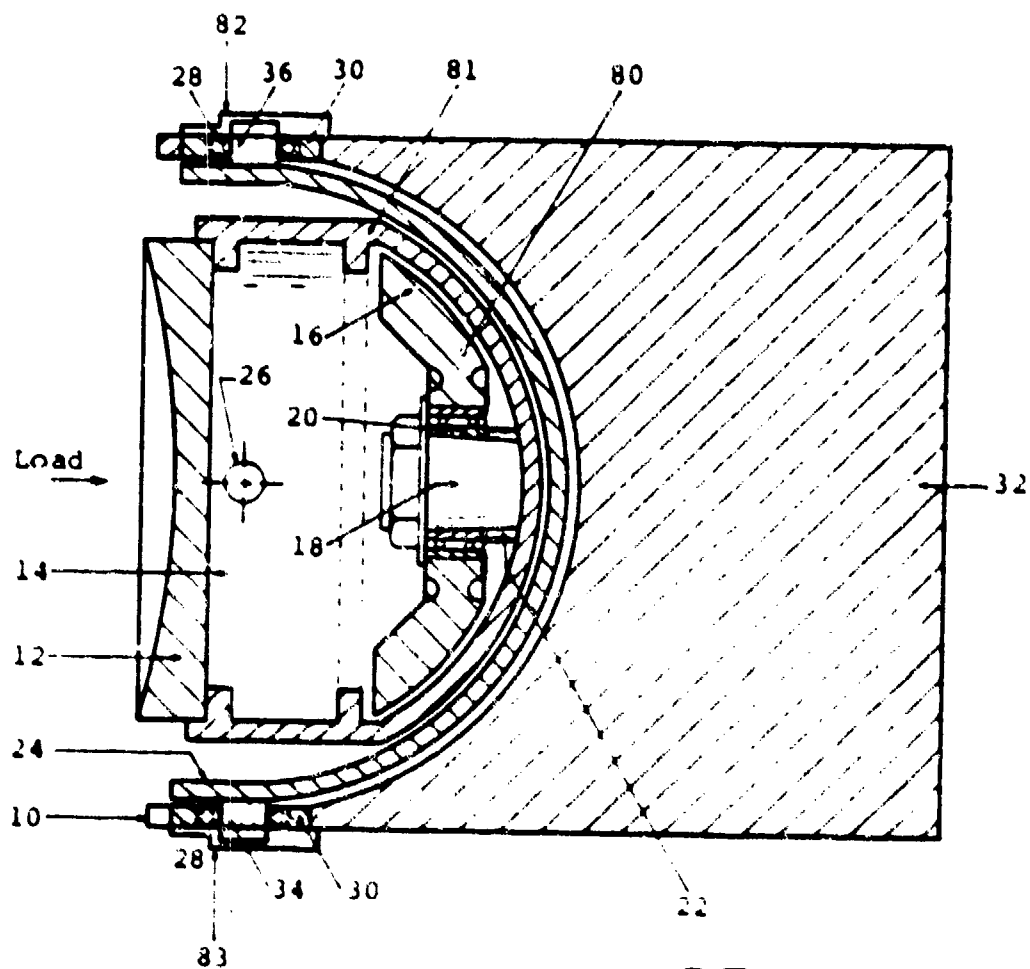


Figure 1.

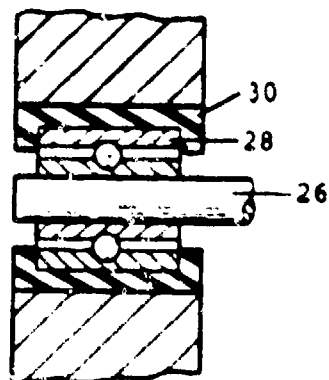


Figure 2.

Figures 1 and 2. Cardan mechanization and bearing protection device.

A gyro rotor (16) is mounted on a tapered shaft (18) secured to hemispherical gimbal (14). A compliant spacer (22) is used between the rotor spin bearing stationary housing (20) and inner gimbal (14). The compliant spacer may be an elastomeric or metal bow type washer. This concept allows the rotor to seat against the inner gimbal housing during high-g acceleration loads. Reverse acceleration loads move the rotor forward into a latched position. If the tapered shaft concept is used, the spin bearings must be designed to carry the impact of the reverse loads.

The rotor web (80) may be designed to have sufficient flexibility so that the forward and reverse shock loads will cause the momentum ring (16) to bottom against the inner hemispherical gimbal (14) during the forward shock and against the gimbal stop (81) during the reverse shock. This concept allows the spin bearing housing to be rigidly secured to the inner gimbal shaft (18).

Inner gimbal (14) is secured to an outer gimbal (24) by a pair of shafts (26), Figure 2. Both ends of shaft (26) are encompassed by a bearing (28) and an elastomeric member (30) that is installed between the gimbal (24) and bearing (28). Outer gimbal (24) (Figure 1) is secured to platform housing (32) by a pair of shafts (34) and (36). Compliant spacers (30) are installed between bearings (28) and platform housing (32).

In the concept shown in Figure 1, a high-g load such as a high velocity projectile, applied to the platform will cause gyro rotor (16) to either overcome the spring constant of compliant spacer (22) and, consequently, move the rotor assembly to rest upon gimbal (14) surface, or the acceleration load will overcome the rotor web (80) flexibility and will cause the momentum ring (16) to bottom against the inner gimbal during forward shock. Simultaneously, the entire gimbal load will transfer through the spring constant of the compliant member around each bearing of the gimbal assembly, thus, causing hemispherical gimbal (14) to rest upon gimbal (24). Compliant bearing suspension transfers gimbal (24) load to platform housing surface (10). Thus, the launch loads, both in launch direction and transverse, are supported by the gimbals and the platform housing (32). The reverse shock load will cause rotor (Web Concept) and gimbals to move forward and seat against rotor reverse stop (81) and outer gimbal reverse stops (82), (83) and identical inner gimbal stops not shown. The reverse gimbal assembly shock

loads are supported by the reverse stops and housing (32) thus protecting all bearings. After the launch phase, the deceleration g-loads and compliant suspension spring constant returns the gimbals and gyro rotor to original pre-launch positions. The gimbals are now ready for stabilization.

If the above compliant suspension spring constant does not provide sufficient stiffness and damping as required to return the gimbals to the original stable position, prior to the stabilization and guidance phase, a snap-lock mechanism is provided in conjunction with elastomeric bearing housing mounts to lock the gimbal bearing assemblies of the gimbal platform into a rigid, stable position. The gimbal snap-lock mechanism, illustrated in Figure 3, includes a rigid bearing outer ring housing (36) secured to shafts (18) and (20--not shown) through the bearing housing assemblies. Shafts (18) and (20) outer bearing housings are provided and an elastomeric ring linear (21) thereabouts. A rigid shoulder surface (42) is provided on housing (22) and compliant complimentary surface (43) is provided on member (36). A snap-lock element (44) is secured to and extends from housing (22).

After launch, the peak deceleration force acting on the projectile or missile and the spring constant of the elastomeric ring linear (21) will move rigid ring bearing housing (36) forward to seat against reverse stop (40) and shoulder (42). The snap-lock element (44) will snap in and seat against rigid bearing housing flat surface (36). The gimbal assembly deceleration shock load is absorbed by the housing reverse stop (40) and housing (22). The deceleration levels and the compliant spring constant will move the gimbal assembly toward the rear and firmly seat it against the snap-lock element (44). The deceleration loads will maintain snap-lock (44) seated firmly against ring bearing housing (36), thus freeing shafts (18) and (20) from reverse stops (40) and (46--not shown). Therefore, the snap-lock mechanism maintains the gimbal assembly in a very stable axial and transverse position during the stabilization period.

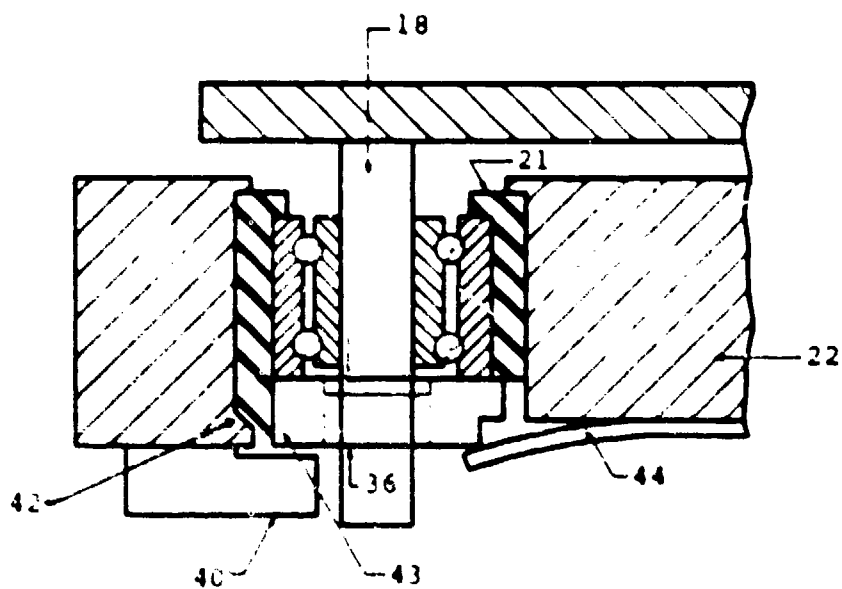


Figure 3. Snap-lock mechanism for High-G Gimbal.

B. HOOKE'S JOINT ATTITUDE GYRO MECHANIZATION.

The second mechanization studied is the Hooke's Joint Concept. The Hooke's Joint Gimbal Concept is illustrated in Figure 4. A high-g launch load will cause rotor (46) either to compress compliant spacer (50), or the rotor web may flex to seat on gimbal (44). Gimbal (44) load subsequently will transfer through bearing compliant housing (58) and seat on ball (52). Ball (52) load will transfer through bearing compliant housing (66), and (68--not shown) and seat on support cavity (53). After launch, deceleration loads and compliant spring constants return gimbal (44), ball (52), and rotor (46) to pre-launch positions.

C. HOOKE'S JOINT RATE MODE MECHANIZATION.

A third mechanization studied is the Hooke's Joint Concept proposing to use rate mode stabilization. The Hooke's Joint rate mode stabilization gimbal concept is shown in Figure 5. Rate sensors, such as the Honeywell GG 1102 vibrating wire (3) are mounted to gimbal (2) with each sensor secured 90 degrees apart. The electronics for each mechanical rate sensor assembly are remotely located in the gimbal housing. The torquers consist of permanent magnets (4) mounted on ball (5) and torquing coils (6) which are secured to gimbals (2) and (7). Error signals from sensor (1) applied to the torquing coils create gimbal torques to provide gimbal rotational movement about pitch and yaw axes. Retractable latching type electrical actuated pins are installed in ball (5) to maintain gimbals (2) and (7) alignment prior to stabilization.

D. REACTION-JET TORQUER.

A reaction-jet torquer concept is studied as an alternate mechanization to control gimbal movement for the Cardan Concept. The reaction-jet torquer uses the gas momentum principle to control the gyro rotor inertial frame of reference, Figure 6.

The reaction-jet torquer consists of a stored gas energy bottle (1), four electrically actuated miniature solenoid valves (2), (3), (4), and (5) - each secured to the inner gimbal (6) 90 degrees apart, a sensor (7) sensitive to incoming illuminated or radiating target signals, and four sonic nozzles (8), (9), (10), and (11) - each secured to the inner gimbal (6) - which are connected to

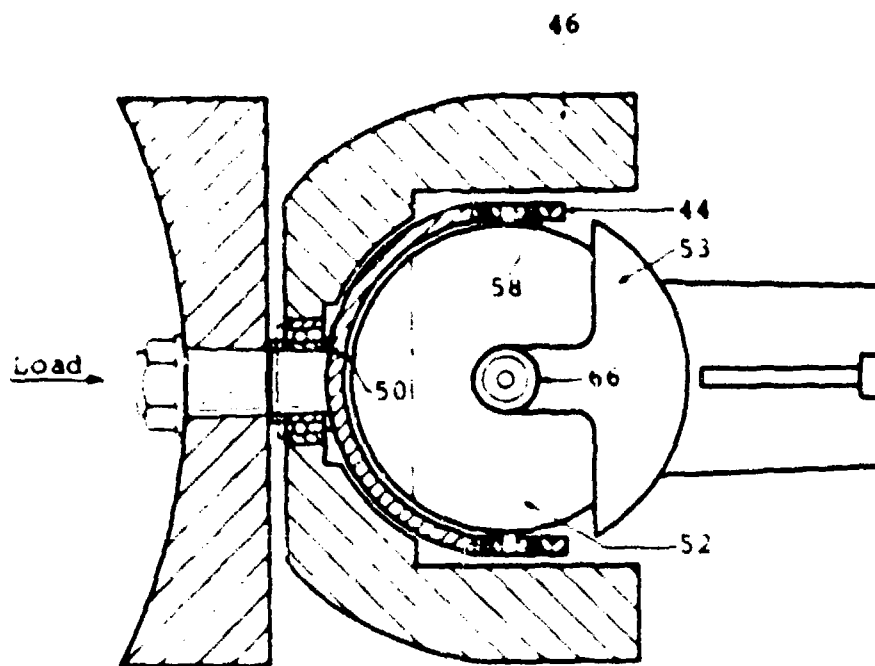


Figure 4. Hooke's joint attitude gyro mechanization.

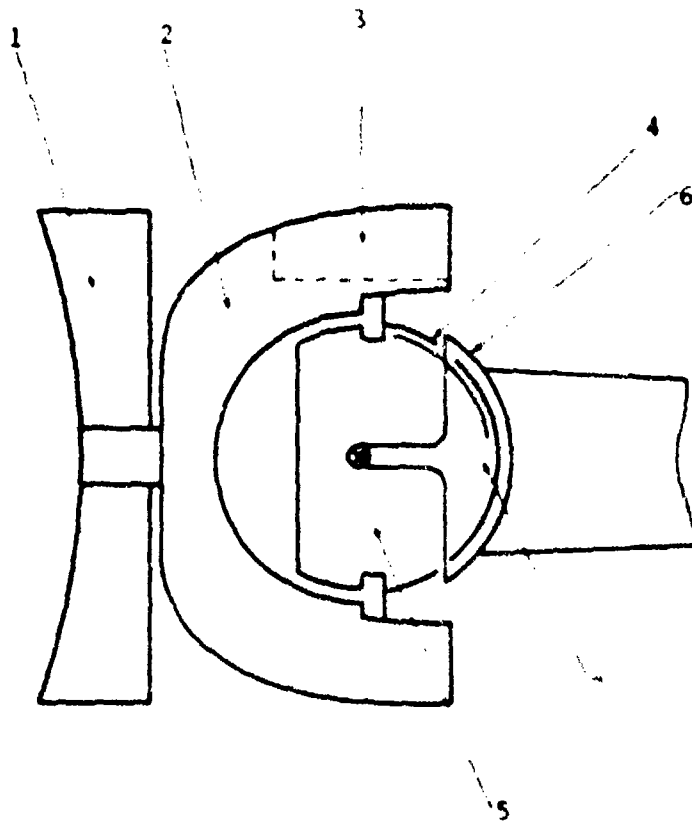


Figure 5. Hooke's joint rate mode concept.

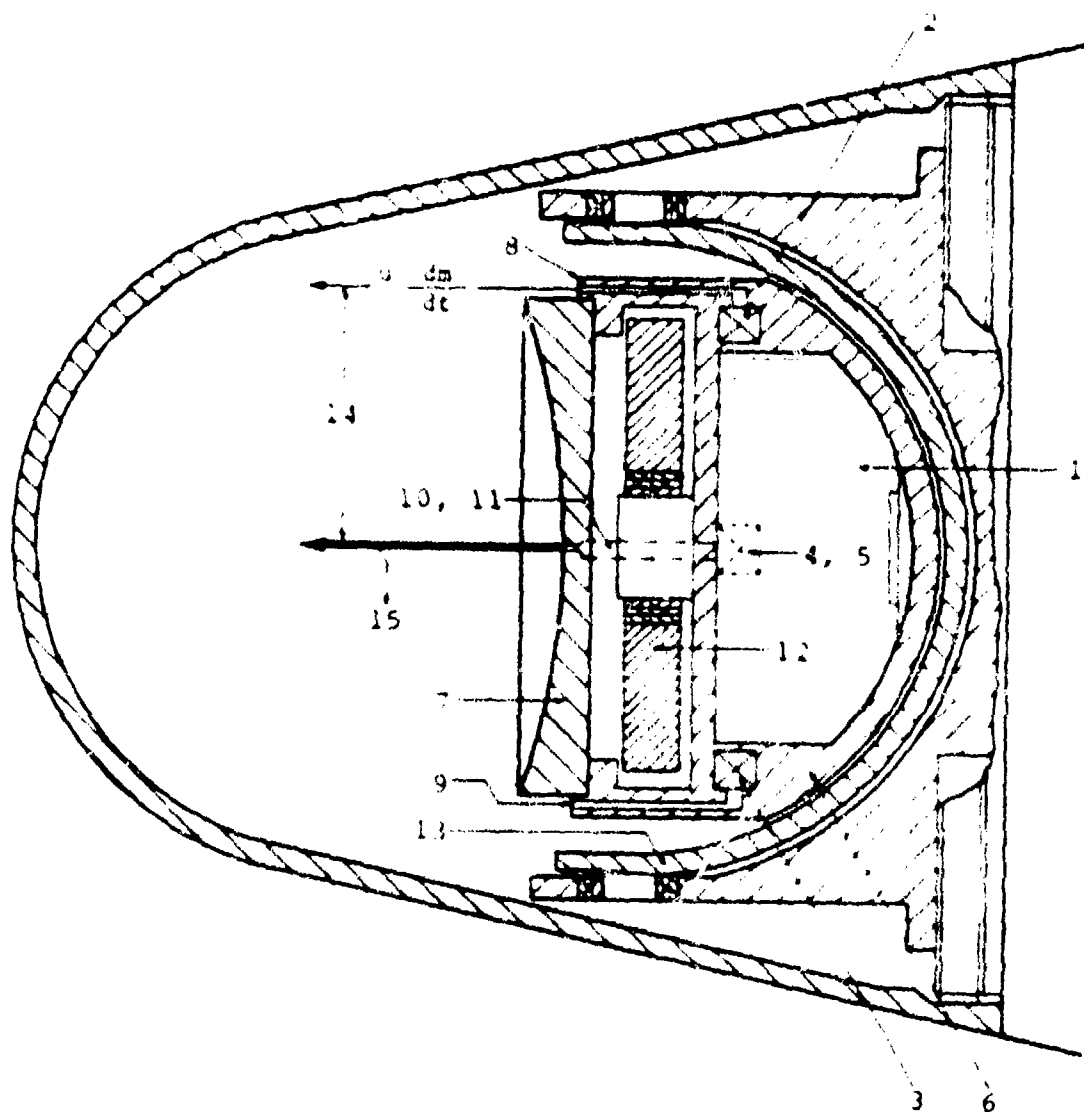


Figure 6. Reaction-jet torquer concept (with high-q gimbal platform).

the gas energy bottle (1) through each solenoid valve (2), (3), (4), and (5) respectively. A gyro rotor (12) is secured to the inner gimbal (6). The outer gimbal is (13); the jet stream moment arm is (14); and the angular momentum vector H is (15).

The stored gas energy in bottle (1) is used to produce the gyro rotor (12) angular momentum. A signal from sensor (7), such as that provided from an external target, will electrically actuate the appropriate solenoid valve, such as (2), thus producing a jet stream of gas through sonic nozzle (8). The gas momentum reaction force acting on gimbal (6) is described by Newton's third law which states

$$F + u \frac{dm}{dt} = m \frac{dv}{dt} \quad (1)$$

where F is equal to the resultant external force acting on the system such as the gravitational force. The term

$u \frac{dm}{dt}$ is called the thrust of the jet stream. The $m \frac{dv}{dt}$ term

is the reaction force acting on gimbal (6). The reaction force on gimbal (6) will be constant if the rate at which the gas is ejected is constant.

If the system's center of mass is equal to the center of suspension, Equation (1) yields

$$u \frac{dm}{dt} = m \frac{dv}{dt} \quad (2)$$

The equation for gyro precession rate under the influence of an applied force (F) is described by

$$\dot{\alpha} = \frac{FL}{H} \quad (3)$$

where L is the jet moment arm (14) and H is the angular momentum of the rotor (12).

Substituting the reaction force $m \frac{dv}{dt}$ of Equation (2) into Equation (3) yields

$$F = \left[m \frac{dv}{dt} \right] \left[\frac{L}{H} \right] \quad (4)$$

whereas the term $m \frac{dv}{dt}$ is the fluidic reaction force acting on gimbal (6) that is required to precess the gyro rotor (12). Rearrangement of Equation (4) yields

$$m \frac{dv}{dt} = \frac{1}{\epsilon} \left[\frac{H}{L} \right] \quad (5)$$

where ϵ is the effectiveness of the nozzle (8). This equation is used to determine the fluidic force required to precess a rotor for a specified jet moment arm, precession rate, and H .

The equations to determine the sonic nozzle diameter, supply pressure, and flow rate for the fluidic force term

$m \frac{dv}{dt}$ in Equation (5) follows:

The mass rate of flow (ideal case) through a sonic nozzle such as nozzle (8)

$$\dot{m} = A_n P_0 \sqrt{\frac{1}{RT} \frac{2}{\gamma+1} \exp \frac{\gamma+1}{\gamma-1}} \quad (6)$$

The force relationship for the nozzle is given by

$$\frac{F}{P_o A_e} = \left[2 \left(\frac{2}{\gamma+1} \right) \exp \frac{1}{\gamma-1} - \frac{P_{atm}}{P_o} \right] \quad (7)$$

The nozzle exit area A_e is eliminated between Equations (6) and (7) to yield

$$\dot{m} = \frac{F \sqrt{\frac{\gamma}{RT} \left(\frac{2}{\gamma+1} \right) \exp \frac{\gamma+1}{\gamma-1}}}{\left[2 \left(\frac{2}{\gamma+1} \right) \frac{1}{\gamma-1} - \frac{P_{atm}}{P_o} \right]} \quad (8)$$

The gyroscopic force $\left[\frac{\dot{L} H}{L} \right]$ in

Equation (5) can be substituted in Equation (8) to yield

$$\dot{m} = \left[\frac{\dot{L} H}{L} \right] \left[\frac{\sqrt{\frac{\gamma}{RT} \left(\frac{2}{\gamma+1} \right) \frac{\gamma+1}{\gamma-1}}}{2 \left(\frac{2}{\gamma+1} \right) \frac{1}{\gamma-1} - \frac{P_{atm}}{P_o}} \right] \left[\frac{1}{K} \right] \quad (9)$$

Equations (6) and (9) can be used to determine the sonic nozzle (8) diameter, supply pressure, and flow rate necessary to develop the required fluidic reaction force

$m \frac{dv}{dt}$, in Equation (5), to precess the gyro rotor for specified gyro design conditions. As an example:

The sonic nozzle reaction force required to torque a gyro rotor with $H = 7 \times 10^5$ gm cm² /sec, $L = 3.5$ cm, $k = 0.94$ (based on experimental results), for a precession rate $\dot{\Omega} = 10^\circ/\text{sec}$, will need a jet stagnation pressure $P_0 = 30$ psig (nitrogen, $\gamma = 1.4$, $T = 530$ R), a nozzle diameter = 0.050 inches and a flow rate = 1.65 SCFM.

The axes used to identify the torque and H - vectors are "right handed" Cartesian coordinates. If a reaction

force $m \frac{dv}{dt}$ is applied from any one of the sonic nozzles

(8), (9), (10), or (11), thus tending to change the direction of the angular momentum vector (15), the H - vector will precess about an axis normal to itself and toward the torque vector at a rate proportional to the applied torque. (A simple rule - the H - vector precesses toward the torque vector.)

The reaction-jet torquer mechanization gives the gyro rotor the capability of tracking a target by using Newton's third law of momentum and sensor (7) logic which identifies the appropriate torquing nozzle that generates the required gimbal (6) reaction force.

3. STABILIZED GIMBAL MECHANIZATION TRADE STUDIES.

A. FACTORS USED IN TRADE STUDIES.

Alternate stabilized gimbal mechanizations and bearing protection devices were considered in the trade studies. Factors used in the trade studies were grouped as: (1) performance, (2) technology risks, and (3) cost. Thus, in studying the various mechanizations, certain performance requirements had to be met. Where comparable requirements and performance could be achieved, the risk in meeting the high-g gimbal launch environment was the determinant. Where the survival risk was not the determinant, potential cost was considered.

B. HOOKE'S JOINT VERSUS THE CARDAN GIMBAL MECHANIZATIONS.

The Hooke's Joint rate, the Hooke's Joint attitude and the Cardan Attitude mechanizations were studied.

The described rate mode gimbal Hooke's Joint configuration could be adapted to the rate stabilized platform concept. However, the choice of rate sensors that can survive 10,000 g launch shock is limited and has deficiencies in zero rate error magnitudes and stabilities. The Honeywell GG 1102 vibrating wire rate sensor was considered. However, it has zero rate errors of $\pm 2^\circ/\text{sec}$ and has not been fully g-hardened. It will require a further development program to develop the unit so that it will survive the 10,000 g launch environment. The Honeywell GG 1102 rate sensor also would be difficult to incorporate into the Hooke's Joint gimbal structure because of its size and weight. The electronics must be mounted in very close proximity to the vibrating wire for proper operation. The cost of the stabilized platform also would be considerably higher since the cost of a g-hardened rate sensor would exceed that of a sustained free rotor type gyro.

The Hooke's Joint's Attitude configuration would have to be carefully mechanized to minimize the moment arm so the concept could achieve the required sensor diameter and gimbal angle for both axes. The retractable latching type electrical actuated pins installed in the ball to maintain the gimbal's alignment prior to stabilization probably would require some design complexity and additional cost. If the moment arm of the stabilization element could be minimized to approach zero, this concept would offer maximum sensor diameter and full ± 45 degree gimbal angle in both axes. It may be other Hooke's Joint mechanization that approach this moment arm configuration criteria. The larger sensor diameter size is significant for ultimate seeker performance and the full two-axes gimbal capability will simplify the integration of the seeker into the complete weapon.

The Cardan stabilized attitude gimbal concept offers excellent inner gimbal balance and the advantage of designing for a smaller rotor. The concept does offer a short moment arm to maximize sensor diameter size. However, a disadvantage of this mechanization is the sensor's inner gimbal axis field of view which is restricted to ± 25 degrees.

The elastomeric bearing protection device, with the snap-lock mechanization, if necessary, is a very inexpensive mechanization for High-G gimbal platform applications. The elastomeric bearing suspension concept with the hemispherical gimbal support during the high-g launch period offers a platform design that should reap substantial cost reduction with inexpensive fabrication methods. The elastomeric suspension concept with its low piece part count lends itself to good high production yields, low cost, excellent probability of surviving the high-g launch environment, and an acceptable performance during the stabilization period.

4. CONCLUSIONS AND RECOMMENDED CONCEPT TECHNOLOGY DEVELOPMENT.

The Cardan Gimbal Concept is recommended and is selected to prove the technological feasibility of the elastomeric bearing suspension mechanization of supporting a heavy sensor in a 10,000 g launch environment. The Cardan Concept is selected because of its maximum sensor diameter size, the short inner gimbal moment arm and the smaller rotor size. Also, an uncomplicated retractable latching pin installed between the gimbals and the support housing is used to maintain gimbal alignment prior to stabilization.

The gyro wheel bearings will be hard mounted to the inner gimbal shaft. The wheel inertia ring support web will have sufficient flexibility to allow the wheel inertia ring to bottom against the inner gimbal assembly during the 10,000 g launch and against the sensor gimbal stop during the 1000 g rebound shock. The bearings will have sufficient load capacity to support the lateral shock loading. The gyro rotor will be energized to approximately 4500 rpm by compressed gas which will be stored in a gas bottle mounted behind the gyro assembly. Spin up time will be less than one second. Gas will be released and the gimbal will be uncaged by electrically operated squibs. The wheel speed will be sustained at 4500 rpm by a small hysteresis motor for the required 70 second mission time. The sustainer motor's 300 Hz power will be obtained by using a solid state dc to ac converter power supply located in the frame behind the gyro assembly. Input to the converter will be ± 15 vdc.

The sensor assembly will be mounted to the inner gimbal assembly and will precess with it.

The gimbal assembly will provide a momentum stabilized platform for the sensor with a gimbal freedom of ± 25 degrees in yaw and ± 45 degrees in pitch. Power and signal leads to the sustainer motor, torquers and pickoffs will be connected to the gimbals probably through roller flex tapes.

The sustainer motor will maintain the gyro wheel at approximately 4500 rpm to provide 3×10^6 gm cm²/sec momentum. The sustainer motor will be a small hysteresis motor mounted on the inner gimbal assembly. The hysteresis motor will have a maximum developed torque of approximately 10,000 dyne cm which will be sufficient to overcome the friction and windage torques of the momentum wheel. Maintaining the wheel speed at 4500 rpm by the sustainer motor will make it unnecessary to monitor wheel speed for torquer scale factor correction. Power to drive the motor will be derived from the ± 15 volts dc power.

Two permanent magnet torquer assemblies, one for each axis, will be used to provide the required 10° /sec torquing rate. Samarium cobalt magnet material will be utilized in the assemblies to minimize the volume and weight.

The outer gimbal torquer magnet assembly will be mounted on the housing with the coil assembly mounted to the outer gimbal. This minimizes the torquer contribution to the outer gimbal cross axis inertia. The inner gimbal torquer magnet assembly will be mounted to the inner gimbal and its coil assembly also will be mounted to the outer gimbal. This arrangement allows counter balancing of the magnet assembly by combination of counter balance weights mounted on the sensor. The torquers as configured will produce approximately 523,000 dyne cm of torque for 1 ampere of current with a power dissipation of 10 watts. This torque will produce the required 10° /sec precession rate with a 3×10^6 gm cm²/sec wheel momentum.

Gimbal angle position will be measured using potentiometer pickoffs. These provide a dc bipolar voltage output when excited with the available ± 15 vdc. Scale factor will be 0.33 volts/degree. Position accuracy will be within ± 0.5 degrees. Potentiometer wiper travel will be made ± 45 degrees for both axes to provide the same pickoff scale factor in the pitch and yaw axis. The resistance element will be conductive plastic and the wiper will be a multifingered configuration made from palaney which is a platinum, paladium, and gold material made by the Ney

Company. This resistance element wiper, combination should provide a rugged potentiometer with the low friction and low noise characteristics required for this 10,000 g environment.

5. RECOMMENDED PROGRAM.

The development of a hardened 10,000 g gimbal system using the recommended technological concept as a sensor platform is recommended. The proposed concept for a millimeter wave type seeker is unusual in that it is the first feasible program to attempt to harden a two-axes gimbal platform for cannon launch type environment. Therefore, a development program is necessary to demonstrate and verify the technological feasibility of the elastomeric bearing protection device and its load support mechanization. The program is necessary also to identify other critical components and recognize areas requiring further study.

Contract DAAK40-79-C-0104 was awarded to Honeywell Avionics Division, March 1979, to fabricate, assemble, and functionally test gimbal hardware, stabilizing element hardware with drive electronics, the torquer assemblies, and gimbal position sensors. MICOM High-G gun launch and soft recovery analysis will verify the proposed High-G platform concept technology.

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3. Invention Disclosure "Reaction Jet Torquer," AMPC 3832, 24 February 1978, Aubrey Rodgers and Escar L. Bailey.

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